Choosing a Suitable Projection for Navigation in the Arctic

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Abstract. Nowadays, navigation at sea is based on Electronic Chart Display and Information Systems - ECDIS that allow for the use of a limited number of projections. As navigation in the Arctic Region becomes a reality due to the progressive melting of the Polar Ice Cap, the re-examination of the most suitable projections for navigation in the Arctic becomes timely relevant. A number of projections are proposed in the literature for this area. In this work the selection is based on an analytical approach utilizing three criteria: the control of the magnitude of distortions within acceptable limits, the shape of Great Circles (GCs) and Rhumb Lines/Loxodromes and the shape of the Graticule lines portrayed on the chart. The analysis carried out shows that in order to fulfill the set criteria Arctic area should be divided into Arctic and sub-Arctic Regions.

Keywords: projections, navigation, Arctic Region

1. Introduction

Electronic charts are prevailing over their paper counterparts for navigation at sea. There are two basic types of electronic charts. Those that comply with the International Maritime Organization's (IMO) requirements for vessels, known as the Electronic Chart Display and Information Systems (ECDIS) and all other types of electronic charts regarded generically as Electronic Chart Systems (ECS). A basic requirement of the ECDIS performance standards is to have Electronic Navigational Charts (ENCs) installed for the intended voyage. ENCs are official vector charts conforming to the specifications of the International Hydrographic Organization (IHO) issued by or on behalf of a national hydrographic office.

The IMO performance standards for ECDIS do not provide for the employment of specific map projections. Navigation with ECDIS has in most cases

assumed use of the Mercator projection, since this projection is applicable for the current area of ENC coverage. As a result, all ECDIS and ECS manufacturers have developed systems that use the Mercator projection and in some cases other projections. This is the display capability that has been given approval by the type approval authorities (ARHC2-08A 2011). The Electronic Navigational Chart (ENC) data collected by Hydrographic Offices in support of ECDIS have no dependence on specific projection giving way to the use of any projection that will be considered as suitable. It is noted that the lack of detailed recommendations on the use of specific map projections in ECDIS does not cause any problem on its function to contribute to the computations required for safe navigation. This is due to the fact that computations in ECDIS are conducted analytically on the surface of the reference ellipsoid (WGS84). In traditional navigation methods, where the Mercator and Gnomonic charts are used due to their inherent characteristics to portray Rhumb Lines (RLs)/Loxodromes, and the Great Circles (GCs)/Orhodromes with straight lines, graphical work on the surface of the projection is required. Nevertheless the lack of standardization on the employment of specific map projections in ECDIS has resulted in the relaxed use of projections and their parameters in many commercial ECDIS systems, which - in some cases - cause remarkable distortions and misinterpretations of the reality (Pallikaris and Tsoulos 2009).

As navigation in the Arctic Region becomes a reality due to the progressive melting of the Polar Ice Cap, the selection of a suitable projection for navigation in the Arctic must be revisited. More specifically since the projections used in ECDIS, such as the Mercator, cause considerable distortions and in order to ensure commonality of display and simplify the task of both the user and the type approval authorities, there is a need for standardization of the display through the use of suitable projections for the Arctic and the sub-Arctic areas. The factor of high latitudes directs nautical cartographers to consider the Arctic Region as a navigation area with special characteristics. The study area for this paper extends from 50° to 90° [lat] although the Arctic Region itself is considered to be north of the 68th parallel. This is due to the fact that it is necessary to address the issue of the selection of suitable projections for the sub-Arctic Region as well.

The navigators' traditional way of observing a charted sea area is using the Mercator projection with meridians perpendicular to the parallels. This pattern of straight orthogonal graticule lines – besides the eventual contribution to navigation - has the advantage that allows for direct conclusions on the relative geographical location between any two points on the chart. In the polar areas the situation is different. Here the meridians are converging towards the poles, which are the centers for the concentric latitude circles. The extreme convergence of the meridians makes it inappropriate or

impossible to determine directions on these charts. A compass line will be curved and will differ considerably from a great circle, even at short distances. Visual bearings cannot, or only with inadequate accuracy, represent a compass line on the chart. This means that the Mercator chart becomes useless at higher latitudes as the compass lines become less usable. Another disadvantage with the Mercator chart is the North – South variation in scale, which results in considerable errors in distance measurements and area distortion. From the above analysis, it becomes evident that due to the disadvantages of the Mercator projection, it will be necessary for the ECDIS to utilize other projections more suitable for the area concerned.

The paper is organized as follows: *Section 2* includes a literature review of the projections that may be used for navigation in the Arctic. In *Section 3*, the identification of the criteria and the approach for the selection of a suitable projection are presented. *Section 4* elaborates on the implementation of the analytical approach in the Arctic Region and the sub-Arctic Region. *Section 5* discuses the results of the analysis followed by the conclusions.

2. Background - Projections for the Arctic Region in Cartographic Literature

Special consideration is given to the selection of projections for the Arctic because the projections commonly used become special cases with unique features (American Practical Navigator 2002):

- *Cylindrical projections* with their axis parallel to the earth's polar axis are characterized by excessive distortion and the rapid change of scale. Such projections cannot be carried to the poles.
- *Conic projections* with their axes parallel to the earth's polar axis are limited in their usefulness for polar charts because parallels of latitude extending through a full 360° of longitude appear as arcs of circles rather than full circles. The usefulness of such projections is also limited by the fact that in some of them the pole appears as an arc of a circle instead of a point. However, by using a parallel very near to the pole as the higher standard parallel, a conic projection with two standard parallels can be made. Such a projection, called a modified Lambert conformal projection or Ney's, is useful for polar charts.
- *Azimuthal projections* are in their simplest form when tangent at a pole. This is because the meridians are straight lines intersecting at the pole, and parallels are concentric circles with their common centre at the pole.

Based on the above the principal considerations in the choice of a suitable projection for polar navigation are conformality, great circles representation, scale variation, meridian representation and shape and position of the area concerned. The projections commonly used for polar charts are: the modified Lambert Conformal, the Gnomonic, the Stereographic and the Azimuthal Equidistant. These projections are similar near the pole. They are essentially conformal and a great circle on each is nearly a straight line. As the distance from the pole increases, however, the distinctive features of each projection become apparent (American Practical Navigator 2002).

3. Identification of the Criteria for the Selection of a Suitable Projection in the Arctic

Based on the above bibliographical information one could proceed by simply choosing a projection among those suggested. We opted for another - namely the analytical - approach due to the following reasons:

a. The selection of the suitable projection should be based on a number of criteria, which are quite relevant to the angular, area and distance distortions inherent in each projection

b. These distortions vary with the latitude and their variance is not constant. The analytical approach is the only way to quantify each kind of distortion and to determine the area where the set criteria are satisfied

c. Besides the above and particularly for the Arctic Region there is a need to identify the limit between Arctic and sub-Arctic areas in order to propose the most suitable projection(s) for the latter.

The selection of a suitable projection for use in the Arctic and sub-Arctic Region depends on mission requirements which justify the relative importance of various characteristics. For a relatively small area, any of several projections is suitable. However for a large area the choice is more difficult.

3.1. The criterion of minimization and distribution of distortions

The values of all kinds of distortions (linear, area and angular) depend on the scale distortion on the principal directions of the projection (Maling 1973). For this reason in the approach followed, the maximum desired tolerances are set only for the angular and area distortions. These tolerances – or acceptable limits of distortion – can take the following values:

a. 10°- 12° for angular distortion and to 10% -12% for the area distortion, in order ensure that no serious visual distortion is generated (Bugayevskiy and Snyder 1995)

b. 6°- 8° for angular distortion and to 6% - 8% for the area distortion, in order ensure that no visual distortion is generated (Bugayevskiy and Snyder 1995)

c. Up to 1° for angular distortion and up to 2% for the area distortion, in order to allow for cartometric use of the map/chart (Maling 1973). It is noted that Bugayevskiy and Snyder (1995), suggest even more strict limits such as 0.25°- 0.5° for angular distortion and 0.2% - 0.6% for the area distortion.

It is evident that the tolerance values depend always on the size of the area covered, the corresponding scale and the intended use of the map/chart. According to the existing bibliography this criterion can be satisfied by a Cylindrical, Conical or Azimuthal projection. These projections are studied analytically in order to achieve the maximum possible reduction of area and angular distortions.

3.2. The criterion of the shape of Great Circles and Rhumb Lines/Loxodromes

For better portrayal of the reality the lines showing Great Circles have to be shorter than the corresponding Rhumb Lines/Loxodromes. In addition Great Circles should preferably be straight lines and when curved they should bend towards the Equator and Rhumb Lines/Loxodromes towards the poles.

This criterion can be satisfied by the Conic and Azimuthal family of projections on which Great Circles are shown with shorter lines than Rhumb Lines/Loxodromes. In addition, these projections have the basic advantage of reducing significantly the amount of angular and area distortions of the Gnomonic projection used in traditional navigation.

3.3. The criterion of the shape of the Graticule lines

In navigational systems it is very useful to ensure that meridians are portrayed as straight lines and intersected orthogonally with parallels. Besides the eventual contribution to navigation it allows for direct conclusions concerning the relative geographic location of any point from the overall visual appearance of the area portrayed. On the other hand such conclusions should not depend on the portrayal of the meridians and parallels, which are not always displayed on ECDIS.

The family of cylindrical projections on which meridians and parallels are shown as straight lines intersected orthogonally - as on the Mercator projection - satisfies this requirement. In this approach, the compensation cost of ensuring the desired shape of meridians and parallels, is that the criterion for the shape of Great Circles cannot be satisfied (Pallikaris and Tsoulos 2010).

4. Analytical Approach

4.1. The criterion of minimization and distribution of distortions

In this section, the distortions of Cylindrical, Conic and Azimuthal projections for the Arctic Region are examined. The calculation of the distortions is performed on the WGS84, as this is the reference ellipsoid used in navigation based on Global Navigation Satellite Systems (GNSS). The formulas used are provided by Snyder (1987) and Bugayevskiy and Snyder (1995) and have been double-checked in Matlab. It is pointed out that the difference in distortion values calculated on the ellipsoid and on the sphere is not significant when compared with the size of distortions.

The distortions of Cylindrical, Conic and Azimuthal projections are analyzed and subsequently compared utilizing computation of distortions calculated at one degree interval of latitude. Limits of acceptable values of distortion can be used to select the area range where a particular projection can be adopted.

A number of projections from each family (cylindrical, conic, azimuthal) are studied:

Cylindrical Projections: Mercator (conformal), Cylindrical Equal Area, and Equidistant Cylindrical. A standard parallel at 65^o is selected for all projections.

Conic projections: Lambert Conformal, Conic Equal Area, and Conic Equidistant. In order to minimize the distortion two standard parallels are selected. The latitudes φ1 and φ2 of the standard parallels are selected by using formulas [1] and [2] introduced by Kavraisky and referred by Bugayevskiy and Snyder (1995).

$\varphi_1 = \varphi_S + \Delta\varphi$ [1] $\varphi_2 = \varphi_N - \Delta\varphi$ [2] where: $\Delta\varphi = \frac{\varphi_N - \varphi_S}{k}$ and φ_S and φ_N are the bounding parallels of the map

The use of the constant K leads to the choice of the suitable standard parallels for conical projections. By selecting K = 5 for a rectangular outline with

longer axis north-south, two standard parallels at 58° and 82° are applied to the projections studied. In addition the Modified Lambert conformal projection is evaluated.

Projection	Limits for areal and angular distortion					
	Area: 10-12 %	**Angle: 10°-12°**	**Area: 6-8 %**	**Angle: 6°-8°**	**Area: 2%**	**Angle: 1°**
Cylindrical						
Mercator	64°- 66°	conformal	64°-65°	conformal	65°	conformal
Equidistant Cylindrical	62°- 67°	59°-69 °	63°-66°	61°-68°	65°	65°
Equal Area Cylindrical	equal area	63 °-67°	equal area	64°-66°	equal area	65 °
Conic						
Lambert	50°- 87°	conformal	50°-86°	conformal	80°-83° & 56°-61°	conformal
Conic Equal Area	equal area	50°-86°	equal area	50°-85°	equal area	55°-62° & 81°-82°
Conic Equidistant	50°-87°	50°-88°	50°-86°	50°-87°	52°-67 ° & 77°-84°	53°-65° & 79°-83°
Modified Lambert Conformal (Ney's)	90 °-60°	conformal	90°-62°	conformal	70°-80° & 90° -87°	conformal
Azimuthal						
Ortho-graphic	90°-62°	90°-55°	90°-67°	90°-61°	90°-79°	90°-80°
Stereo-graphic	90°-63°	conformal	90°-68°	conformal	90°-79°	conformal
Equal area	equal area	90°-50°	equal area	90°-50 °	equal area	90°-75°
Equidistant	90°-50°	90°-50°	90°-52°	90°-50°	90°-71°	90°-72°

Gnomonic	90°-75°	90°-55°	90° -77°	90°-61°	90°-84°	90°-80°

Table 1. Arctic region: Areas (φmin – φmax) where the set limits for area and angular distortions are satisfied for each studied projection**.**

Azimuthal projections: five (5) Azimuthal projections are studied: Orthographic, Stereographic (conformal), Azimuthal Equal Area, Azimuthal Equidistant and Gnomonic. All projections are applied with the polar aspect.

Table 1 shows the areas where the set limits for area and angular distortions are satisfied for each projection studied. In general areal and angular distortions for Cylindrical projections are excessive and surpass the set limits except for certain parts of the study area where the set limits/tolerances are satisfied. Areal and angular distortions for Conic projections are less than those of the Cylindrical projections but still exceed the set limits except for certain sub areas where the set limits are satisfied. Areal and angular distortions for Azimuthal projections are considerably lower than those of the Conic and Cylindrical projections and in general satisfy the set limits. A closer look at this table leads to the conclusion that practically unnoticed distortions can be achieved with the Equidistant Azimuthal projection for most part of the Arctic Region. The area between 90° - 72° is covered with maximum area distortion less than 2% and maximum angular distortion 0.95 ° making this projection the most suitable one.

An alternative choice is the Stereographic projection, which behaves comparatively well. Changing the position projection plane will result to lower distortion values for this projection. The analysis carried out shows that there is no need for this provided that the limits set are satisfactorily met by the standard form of the Azimuthal projections where the plane is tangent at the pole. On the other hand for the sub-Arctic Region the table of distortions directs us to look for other more suitable projection(s) that will portray the area covering latitudes from 50° to 75° with minimum distortions.

4.2. Study of map projections for the sub-Arctic Region

As it is pointed out in the previous section the results of the analysis of the distortions for the projections studied lead to the necessity of addressing the issue of projection selection separately for the sub-Arctic Region (50° – 75°) since the area 90° -70° is satisfactorily covered by the proposed projections. For this part of the study Conic and Cylindrical projections are analyzed.

Conic Projections: Lambert Conformal, Conic Equal Area, and Conic Equidistant. In order to minimize the distortion values two standard parallels are selected as discussed earlier at 55° and 70° for all three projections.

Cylindrical projections: Mercator (conformal), Cylindrical Equidistant and Cylindrical Equal Area. A standard parallel at 60^o is selected for all projections.

Table 2 shows the areas where the set limits for area and angular distortions are satisfied. In general areal and angular distortions for Conic projections satisfy the set limits, with the Lambert Conformal and Conic Equidistant projections giving the best results. Areal and angular distortions for the cylindrical projections exceed the set limits that make them visually unobservable and they are satisfied only in small parts of the sub-Arctic Region.

Projection	**Limits for angular and areal distortions**					
	Area: 8 -10%	Angle: 8^o -10^o	Area: 6 - 8%	Angle: 6^o - 8^o	Area: 2%	Angle: 1^o
Lambert conic	50^o-75^o	conformal	50^o-75^o	conformal	52^o-73^o	conformal
Conic Equal Area	equal area	50^o-75^o	equal area	50^o-75^o	equal area	51^o-72^o
Conic Equidistant	50^o-75^o	50^o-75^o	50^o-75^o	50^o-75^o	50^o-74^o	50^o-74^o
Equidistant cylindrical	57^o-62^o	54^o-65^o	62^o-57^o	55^o-65^o	60^o	59^o-61^o
Equal area cylindrical	equal area	57^o-62^o	equal area	58^o-62^o	equal area	60^o

Table 2. Sub-Arctic region: Areas (range of latitude φmin – φmax) where the set limits for area and angular distortions are satisfied for each studied projection.

Concluding and specifically for the sub-Arctic Region, the Lambert Conformal and Conic Equidistant projections are those satisfying the set limits of distortions.

4.3. The criteria of the shape of Great Circles/ Rhumb Lines along with the shape of Graticule lines

The study of the shape of Great Circles and Rhumb Lines is carried out through the computation and portrayal of selected navigational paths in the Polar area on those projections which satisfy the tolerance values set for the first criterion. These projections are:

- The Polar Equidistant (*Figure 2*) and the Polar Stereographic (*Figure 1*) which are suitable mainly for the Arctic region

- The Lambert Conformal (*Figure 3*) and the Conic Equidistant (*Figure 4*) which are suitable mainly for the sub-Arctic Region

In the polar area the Orthodromic navigation is recommended due to the fact that the Orthodromic distance is less than the Loxodromic one. This difference becomes greater as the distance between the departure and destination points increases. In order to provide accurate results for the Orthodromic distances they are calculated as Great Elliptic arcs, which offer higher accuracy than that of the Great Circle arcs (Pallikaris and Latsas 2009).

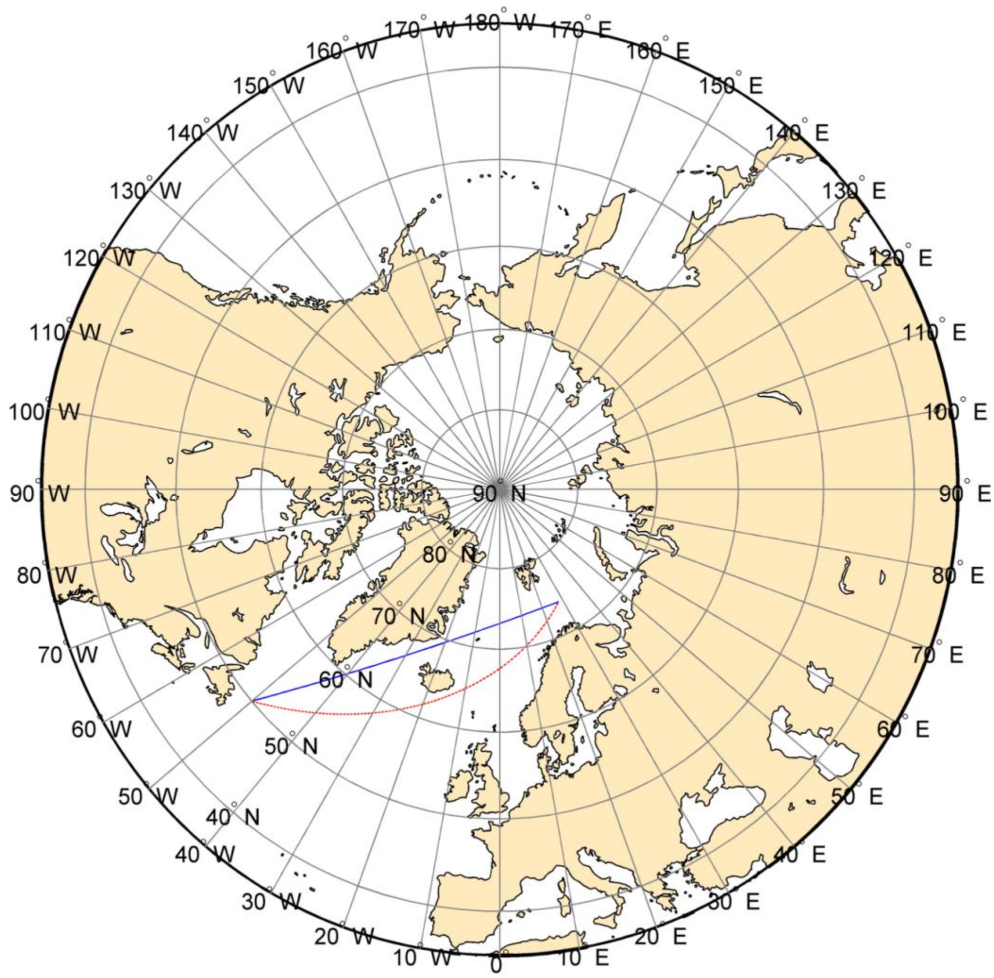

Figure 1. Azimuthal Polar Stereographic projection, Departure point at 50° N, 50° W, destination point at 74° N, 28° E, Orthodromic distance 1550.1 n.m., Loxodromic distance 1557.5 n.m..

With respect to the shape of the graticule lines and more specifically of the representation of meridians and the way they are intersected with parallels, this criterion becomes less important due to the significance of the other two criteria and the fact that – as it has already pointed out – all three criteria cannot be satisfied simultaneously. In any case this last criterion will be taken into account in case it is partially satisfied.

As it is derived from both the distances computed and the shape of the Great Circles, all four projections are considered as suitable due to their distortion characteristics.

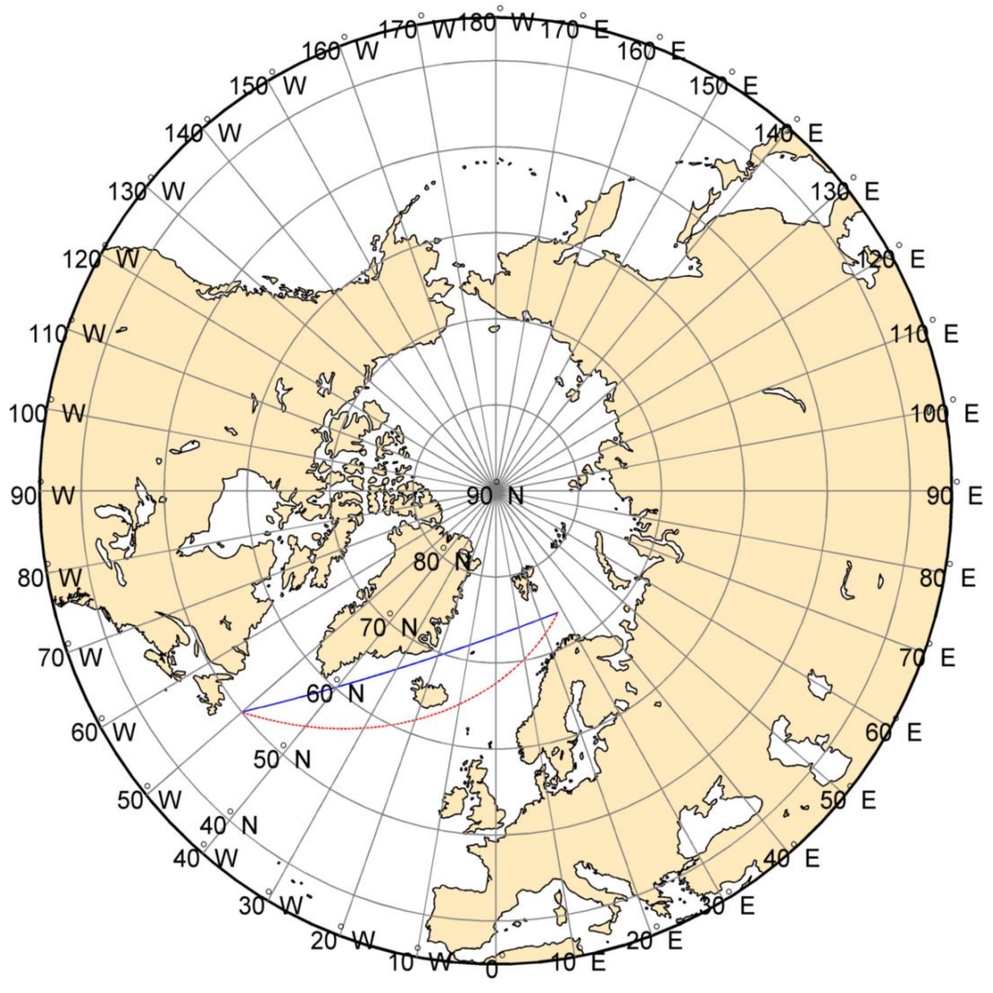

Figure 2. Azimuthal Polar Equidistant projection, Departure point at 50° N, 50° W, Destination point at 74° N, 28° E. Orthodromic distance 1550.1 n.m., Loxodromic distance 1557.5 n.m.

5. Conclusions

The decision on the choice of the suitable projection for a particular map/chart is a problem that cartographers are facing quite often.

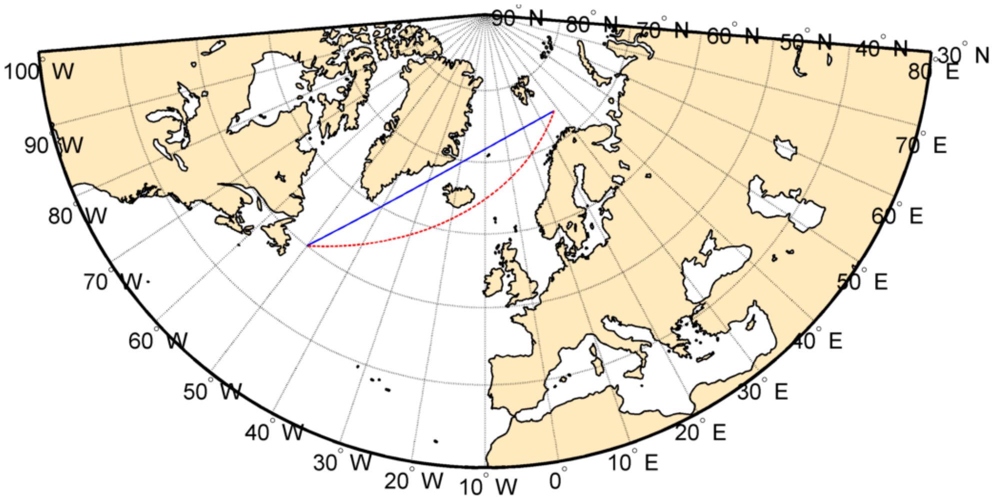

Figure 3. Lambert Conformal projection (standard parallels at latitudes 58 ° and 82°), Departure point at 50° N, 50° W, destination point at 74° N, 28° E, Orthodromic distance 1550.1 n.m., Loxodromic distance 1557.5 n.m.

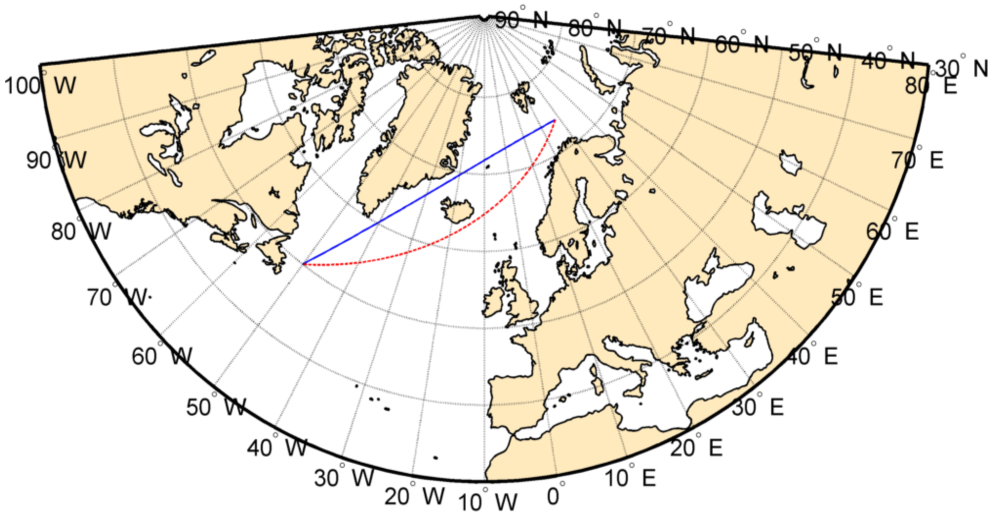

Figure 4. Conic Equidistant projection (standard parallels at latitudes 58 ° and 82°), Departure point at 50° N, 50° W, destination point at 74° N, 28° E, Orthodromic distance 1550.1 n.m., Loxodromic distance 1557.5 n.m.

The primary aim of a logical choice is to select a projection in which “the extreme distortions are smaller than would occur in any other projection used to map the same area” (Maling 1973). This has been the main criterion for the selection of a suitable projection for the Arctic Region in this study. Besides this criterion the indented use of the map/chart determine which property/criterion is important.

Such an effort requires analytical approach for the calculation of the values of each kind of distortion for the projections under consideration. The analytical approach allows for the identification of the geographical boundaries of the areas where the distortions’ values satisfy the specified acceptable limits. In this project the aforementioned characteristic led to the “separation” of the study area in the Arctic and sub-Arctic Regions for which different projections have been chosen and proposed.

More specifically, for the Arctic Region the Azimuthal Polar Equidistant projection and the Azimuthal Polar Stereographic projection are proposed. For the sub-Arctic Region the Lambert Conic Conformal projection and the Conic Equidistant projection are considered as the most suitable ones. All four projections proposed can be used for both the traditional nautical chart and the ECDIS and are considered as the starting point for further study of specific ECDIS requirements (i.e. radar integration with ENC).

Given that most of the ECDIS systems do not include these projections either as a system or a manual choice, it is considered necessary that the specifications concerning the performance requirements of ECDIS be revised in order to include the proposed projections for the Arctic and sub-Arctic Regions.

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